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Environmental Life Cycle Impact Assessment of Transportation Infrastructure: A Multi-Case Study in International Perspective

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Abstract:

Although transportation infrastructure promotes the continuous development of the world economy, it is also responsible for serious pollution problems. These are studied in the analysis of five transportation infrastructure projects from Bosnia, Pakistan, and China, and their environmental emissions and impacts using an environmental impact assessment model of transportation infrastructure based on life cycle analysis. This shows that: (a) the main reason for the negative environmental impact of transportation infrastructure is the use of energy and complex materials, of which the use of lime soils has the biggest influence on global warming; and (b) frequent overhaul maintenance has a greater impact on the environment compared to daily maintenance. Our findings provide governments from all countries with a scientific basis for formulating policies for energy conservation and reduction in transportation infrastructure emissions.

Keywords:

Energy saving; Emissions reduction; Life Cycle Impact Assessment; Transportation Infrastructure; Environmental Impact Assessment.

1 Introduction

Transportation infrastructure plays an important role in the urban development and economic growth of most national economies (Mohmand et al., 2017; Xie et al., 2017). Mainly comprising roads, railways, ports, and airports, it enables most social and commercial activities (Sun & Cui, 2018). However, while the provision of such infrastructure continues to expand, its high energy consumption and pollution is a continual concern (Shi et al., 2012; Wang et al., 2020), as the construction and operation of transportation infrastructure consumes many resources and energy and produces many solid wastes, all of which are major sources of environmental problems (ERI, 2010).

Previous studies have addressed these environmental problems mainly from a (regional) micro perspective, neglecting the analysis of the environmental impact of transportation infrastructure from a broader international perspective. For example, Sun and Cui (Sun & Cui, 2018) analyze four Chinese municipalities and discuss the economic and environmental benefits of transportation infrastructure under environmental constraints. (Melanta et al., 2013) use the U.S. Maryland highway to estimate greenhouse gas emissions and other air pollutants that occur during the construction of transportation infrastructure.

However, the environmental damage caused by transportation infrastructure is a challenging problem that cannot be faced by a single country or region alone; by analyzing these environmental issues from an international perspective, we can identify common problems and more effective solutions. Specifically, a multi-case study that emphasize construction, evaluation, and comparison can makes inductive case study consistent with theory constructed in deductive research (Liu et al., 2020). At the same time, multi-case study allows researchers to find knowledge related to practice through comparative analysis of multiple actual cases (Eisenhardt & Graebner, 2007), which helps to constructing an easy-to-understand theoretical framework and solve environmental problems in the construction of international transportation infrastructure more effectively. Additionally, most studies also analyze the impact of transportation infrastructure solely during its construction phase (Dimoula et al., 2016; Giustozzi et al., 2015; Guo et al., 2017), failing to consider the post-construction consequences. Finally, existing transportation infrastructure environmental impact assessment models are quite limited in their measurement capability of the most relevant types of potential impacts (Peng et al., 2016).

Hence, this study analyzes a wide range of environmental impacts of transportation infrastructure, with an international perspective based on a life cycle approach and beyond the construction stage. First, we select five case studies from Bosnia, Pakistan, and China. Second, we propose an environmental impact assessment model of transportation infrastructure based on life cycle analysis to calculate the environmental emissions of transportation infrastructure based on the consumption of the materials and energy of the five case studies. Finally, we provide policy suggestions for reducing the environmental impact and emissions of transportation infrastructure as potential guidance for governments to achieve such environmental protection outcomes as the EU's 2030 Climate Goals and China's 2030 Sustainable Development Goals.

2 Literature review

2.1 Research into TI Environmental Impact Assessment

The environmental impact assessment (EIA) of transportation infrastructure (TI) is aimed at predicting and evaluating the impact that transportation projects may have on the environment during their construction and operation stages (Wenger et al., 1990). Since the 1970s, the U.S. and some European countries and have registered the carbon emissions of their larger TI projects (Barandica et al., 2013), which has allowed some national-level environmental emission databases to be created (Khan et al., 2002; Krantz et al., 2015). Consequently, several research studies have conducted the life cycle environmental impact assessment (LCIA) of transportation infrastructure (TI). (Choi et al., 2016), for example, make a LCIA of three types of pavements, while

(O'Born, 2018) conducts a comparative analysis of the environmental impact of wooden and concrete bridges. In both cases, their analyses of environmental emissions help to reduce the impact of the construction and operation phases, while also having important economic implications.

Also in the field of TI, (Colorni et al., 1999) propose some decision support systems for enhanced environmental impact assessment (EIA). (Banar & Ozdemir, 2015) conduct an EIA of Turkish railway infrastructure and evaluate the effects on abiotic depletion (i.e. acidification, eutrophication, global warming, human toxicity, and freshwater toxicity). (Dabous et al., 2017) perform an EIA of a bridge in Ontario, Canada, evaluating the carbon dioxide (CO_2) emissions and energy consumption in considering the phases of bridge overhaul and replacement. These examples illustrate how the development of EIA models has expanded the current TI research field and, at the very least, raised awareness of the need to reduce the transportation industry's increasing environmental emissions.

2.2 Application of Life Cycle Analysis (LCA) in Environmental Impact Analysis

Both the "ISO14040: Environmental Management - Life Cycle Assessment - Principles and Framework" and the "ISO14041: Environmental Management - Life Cycle Assessment - Target and Scope Determination and Stock Analysis" state that impact indicators and assessment methods depend on the scope of the LCA. LCA can break down complex systems information into smaller functional units. While this is convenient for establishing a macro-to-micro environmental assessment framework, it also intuitively reveals the environmental impacts of materials and energy flows.

In the field of environmental impact assessment (EIA), LCA often adopts a "cradle" to "grave" approach. For TI, these stages span from raw material extraction to transportation, production, use, and disposal. For example, (Li et al., 2019) evaluate the carbon emissions of four different types of buildings (hospitals, schools, residential, and commercial housing) based on the LCA approach − their research showing that rebar greatly contributes to carbon emissions during the construction phase of buildings. Chang and Kendall (Chang & Kendall, 2011) also examine the greenhouse gas (GHG) emissions generated by TI, again showing the production processes of materials to be the main source of GHG emissions.

LCA principles have also been widely used in TI environmental impact assessment. For example, (Li et al., 2018) study the environmental impact of traffic delays in the TI maintenance and repair stages. (Zhang et al., 2018) assess the impact of different highway asphalt pavements through LCA, finding that the contribution of the asphalt surface layer to global warming generally exceeds 95% of all the impacts analyzed: hence why changing the type of asphalt layers on pavements generally has a significant reduction effect on environmental impact. (Xie et al., 2018) combine LCA principles and genetic algorithms to propose an optimization framework for the maintenance of existing bridges while analyzing their life cycle costs and environmental impacts. Finally, (Inyim et al., 2016) perform a thorough review of the EIA LCA applications of pavements, suggesting that the confirmation of uncertainty factors and environmental assessment indicators can significantly improve the reliability of environmental impact analyses. These, in turn, can provide an accurate basis for sustainable environmental decision-making.

2.3 Research gap

Previous studies mainly use carbon emissions as the sole indicator when analyzing the environmental impacts of TI. Reducing carbon emissions is indeed regarded as providing one of the major means of reducing global warming and climate change. However, there is also a need to pay attention to the environmental impacts of SO_2, NO_x, hydrogen sulfide, and other atmospheric pollutant emissions (Capatina et al., 2012), all of which are present in the TI construction and operation phases.

Therefore, the present study examines a comprehensive set of LCIA indicators and proposes a LCIA model for evaluating TI environmental emissions, a set of energy-saving and emission-reduction strategies is proposed.

3 Research methods

3.1 Definition of the evaluation scope

LCIA is an extensive and multifaceted concept that covers multiple industrial applications; hence, a necessary precursor is to define the research scope. This includes the assumptions made and functional units and system boundaries adopted.

(a) Assumptions made

As many variables are potentially involved in TI LCIA, some assumptions are inevitably needed concerning the use of simplifying parameters.

Firstly, since the materialization stage is the process of transforming construction materials into building entities, the most relevant parameter in this stage is the transportation distance of construction materials. Based on previous case studies, this is assumed to be 60 km from the manufacturing plant to the construction site. It should be noted that, since Simapro has already taken into account energy consumption and environmental pollution during the process from mining to the processing of raw materials of construction, the parameters in this process were not assumed.

Secondly, the major sources of environmental pollution are the energy consumed in operation, and maintenance activity in the maintenance stage. Therefore, the most relevant parameters in the maintenance stage are transportation infrastructure life span and length of the maintenance cycle. The overhaul period of the transportation infrastructure is assumed to be seven years, with three overhaul times during its life cycle. The energy consumption and times of daily maintenance are calculated directly from the maintenance and repair engineering quantity list of each case study project.

Finally, in the demolition stage, the negative environmental impacts of transportation infrastructure are mainly from the energy consumption generated in the process of transport construction waste to landfill. According to previous studies, it is assumed that 70% of construction materials are reused at the demolition stage, and 30% of the materials are sent to landfill for disposal. These parameters are conservative demolition values based on the recovery rate of the industry. The transportation distance of construction waste in the demolition stage is assumed to be 30 km.

(b) Functional units

A functional unit defines how to quantify the environmental impact. The units provide both a reference that correlates the model inputs and outputs, and a consistent measurement standard between different product systems and alternatives (Rebitzer et al., 2004). TI projects have different purposes, elements, coverage, and sizes; hence, to compare and analyze the environmental emissions of different product systems, 1 m^2 of road infrastructure is used as a functional unit. This functional unit allows the environmental impact of all materials and energy input flows involved to be quantified and homogenized. The environmental emission units of various categories are also subject to the same functional unit when defining their corresponding evaluation indices.

(c) System boundaries

A system boundary is a conceptual line that combines all unit processes and basic system flows in the analysis, which is carried out through a set of criteria that include whether the system produces any by-products that must be explained by system expansion or distribution (Finnveden et al., 2009). As a large number of unit processes occur during the entire TI life cycle, it is necessary to define the analysis scope (boundary).

The life cycle boundaries are defined as those involving the TI materialization, maintenance, and demolition stages (Ballesteros-Pérez et al, 2019). The *materialization* stage includes material production, transportation, and construction. Hence, this stage also involves the mining, production, and transportation of various materials, as well as the energy consumption of paving, rolling, watering, and other auxiliary processes. The *maintenance* stage includes routine maintenance in addition to repair processes. Finally, the *demolition* stage consists of the demolition and waste transportation processes. Figure 1 summarizes all these system boundaries.

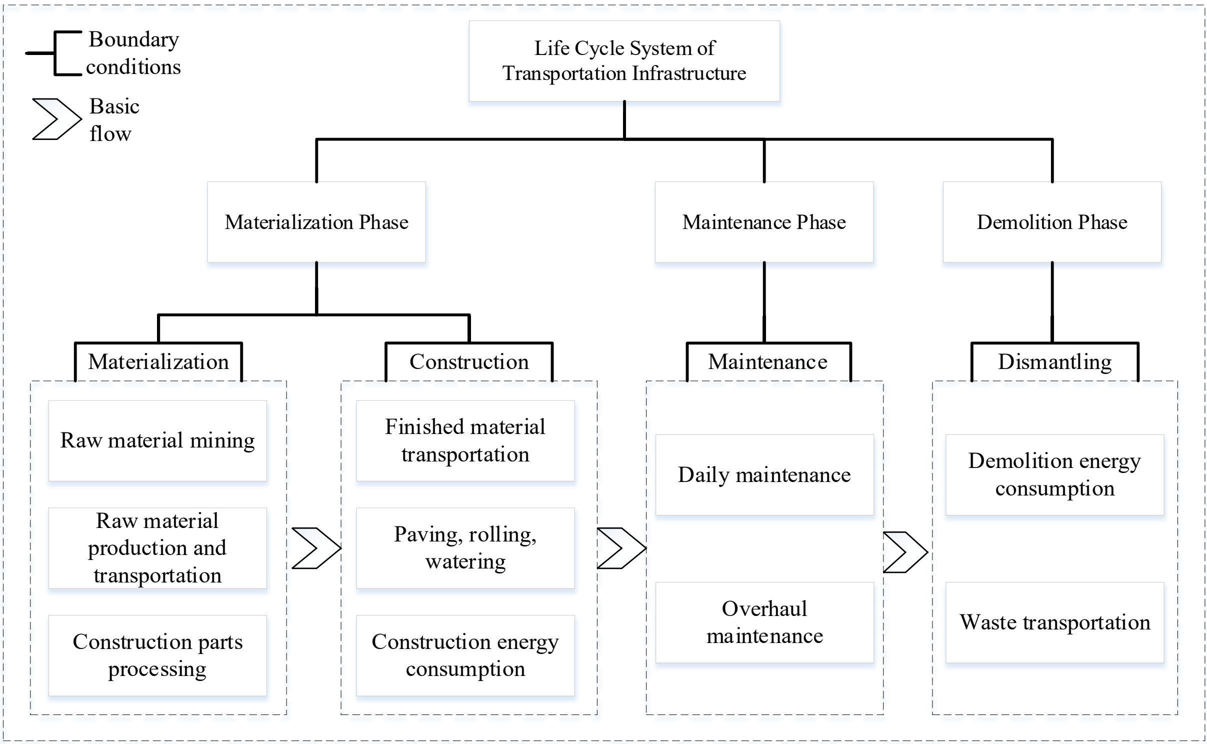

Figure 1. System boundary of the study's LCIA

3.2 Measurement model

The inventory data is classified according to the functional units shown in Figure 1. The proposed calculation model framework is composed of four parts:

(a) Transportation measurement

The measurement units of all the materials in the data list are not the same; hence, it is necessary to unify construction materials as a function of their weight unit when considering their transport. In terms of the materialization stage, the transport measurement of one functional unit is shown in formula (1), while that in the demolition stage is shown in Formula (2).

$$T_{mj} = \sum_{i=1}^{n} \frac{M_{ij}}{L_j \times W_j} \times D_{mij} \tag{1}$$

Where: T_{mj} is the transportation measurement in the materialization stage of the *j*-th project (in t·km/m^2);

M_{ij} is the total weight of the i-th material in the *j*-th project (t);

L_j is the calculated pavement length in the *j*-th project (m);

W_j is the calculated pavement width in the *j*-th project (m);

D_{mij} is the transportation distance of the *i*-th material in the materialization stage in the *j*-th project (km).

$$T_{dj} = \sum_{i=1}^{n} \frac{M_{ij}}{S_j} \times (1 - f_i) \times D_{dij} \quad (2)$$

Where: T_{dj} is the transportation measurement in the demolition stage of the *j*-th project (t·km/m^2);

S_j is the calculated pavement area in the *j*-th project (m^2);

f_i is the recovery rate of the *i*-th material;

D_{dij} is the transportation distance of the *i*-th material in the demolition stage in the *j*-th project (km).

(b) Energy consumption during construction

Some energy consumption can be directly recorded during the construction process, such as construction lighting and onsite offices' power consumption. However, other types of energy consumption also need to be considered. In this regard, the energy consumption of the paving, rolling, and watering processes in the materialization stage is considered as representative to measure the energy consumption of the materialization stage. Details are shown in formulae (3) and (4). These two formulae can also be used to measure the energy consumption in the demolition stage.

$$P_{jk} = \sum_{i=1}^{n} \frac{Q_{ij}}{S_j} \times Y_{ij} \times N_{ij} \quad (3)$$

Where: P_{jk} is the total fuel consumption of construction equipment in the *j*-th project (m^3/m^2);

Q_{ij} is the average fuel consumption per shift of the *i*-th construction machine in the *j*-th project (m^3/one-shift);

Y_{ij} is the number of operating units for the *i*-th construction equipment of the *j*-th project;

N_{ij} is the number of the *i*-th construction equipment in the *j*-th project;

i is the type code of construction equipment.

$$E_{Pj} = \sum_{i=1}^{n} P_{jki} \times \rho_{ki} \times q_{ki} \tag{4}$$

Where: E_{Pj} is the energy consumption of the construction machine in the *j*-th project (MJ/m^2);

P_{jki} is the total fuel consumption of the *i*-th construction machine in the *j*-th project (m^3);

ρ_{ki} is the machine oil density (kg/m^3). Calculated for kerosene, the value is 800 kg/m^3;

q_{ki} is the calorific value of machine oil (MJ/kg). According to the average low calorific value of kerosene, the value is 43.07 MJ/kg.

These equations can also be used to calculate the energy consumption of machine tools.

(c) Maintenance energy consumption

Maintenance energy consumption includes daily maintenance as well as overhaul maintenance. The daily maintenance energy consumption is calculated by

$$E_{mj} = (C_{sj} \times p_c + \sum_{i=1}^{n} E_{xij}) \times \frac{L_j}{S_j \times f_j} \tag{5}$$

Where: E_{mj} is the total energy consumption of the life cycle overhaul maintenance of the *j*-th project (MJ/m^3);

C_{sj} is a single overhaul equivalent to coal consumption in the *j*-th project (t);

p_c is the standard coal calorific value (MJ/t). The calorific value of standard coal is 29,300.6 MJ/t;

E_{xij} is the single-time maintenance of the i-th construction machine consuming energy in the j-th project (MJ);

L_j is the shelf life of the transportation infrastructure (a);

f_j is the overhaul maintenance cycle (a/each-time).

(d) Energy conversion

The database in the evaluation model is collected and sorted according to its energy source. To avoid mixing data and losing consistency, the energy values of the country where each evaluation project is located is converted into a common energy value. In this case, the energy saving potential data is used from the International Energy Agency. Energy saving potential is a very important factor in energy efficiency that can be used for energy conversion between data from different countries. It is calculated as (Hong et al., 2013)

$$E_{co} = E_c \times \frac{E_1}{E_2} \tag{6}$$

Where: E_{co} is the total energy from fuel burning in the country/region of origin of the original database/project (MJ),

E_c is the total energy produced by fuel combustion in the country where the material is produced (MJ);

E_1 is the energy saving potential of the country/region of the original database/project;

E_2 is the energy saving potential in the country where the material is produced.

3.3 Evaluation index

There are numerous EIA indicators − such as global warming, acidification, HH cancer, HH non-cancer, HH criteria air pollutants, eutrophication, ecotoxicity, smog, natural resource depletion, indoor air quality, habitat alteration, water intake, and ozone depletion. Of these, eight of the most representative types are used to analyze TI environmental impact: (1) global warming, (2) acidification, (3) eutrophication, (4) ecotoxicity, (5) smog, (6) natural resource depletion, (7) habitat alteration, and (8) ozone depletion (Table 1).

Specifically, the main reason for global warming is the emission of greenhouse gases such as CO2, CH_4, and PFCs. As a global environmental pollution problem, acidification is the phenomenon of soil and water acidification and environmental degradation caused by acid precipitation caused by man-made pollution. In this study, the emissions of substances such as NH3, HCl, and HF were used to measure acidification. Eutrophication refers to water pollution caused by excessive amounts of nutrients such as NH_3, N and P in a water body. Ecotoxicity is the main indicator that describes the hazardous characteristics of hazardous wastes, which explain the danger of human, animal and plant exposure to certain pollutants in the environment. The remaining indicators are explained in more detail in Table 1.

Table 1. TI EIA indicators

Evaluation index	**Measurement unit**	**Description**
Global warming	g CO_2 eq	Greenhouse gases, mostly CO_2, CH_4, PFCs, HFCs, HCFCs, and SF_6.
Acidification	H+ mmole eq	Includes NH_3, HCl, HF, H_2S, NO_2, nitrogen oxides, SO_2, SO, and H_2SO_4.
Eutrophication	g N eq	Includes NH_3, N, NH_4^+, BOD5, COD, N_2O, nitrate, nitrite, NO_2, nitrogen oxide, P, H_3PO_4, and phosphate.
Ecotoxicity	g 2,4-D eq	Includes 2,4-dichlorophenoxyacetic acid ($C_8H_6CI_2O_3$), $C_6H_{12}O$, mercury, CO, C_2H_4O, hydrocarbons, alkanes, toluene, and fluoride.
Smog	g NOx eq	Includes nitrogen oxides, NO_2, particles (>10µm), aldehydes, chlorinated hydrocarbons, hydrocarbons, aliphatic, and alkanes.

Natural resource depletion	MJ surplus	Includes crude oil, natural gas, hard coal, coal, gas, mines, waste gas, and coal mining.
Habitat alteration	T&E count	Includes the dumping site, surplus material landfill, inert material landfill, waste landfill, and waste dump.
Ozone depletion	g CFC-11 eq	Includes $CBrF_3$, HCFC-22, CFC-10, CFC-12, HCFC-140, and CH_3Br.

3.4 Evaluation tool selection

The development of modern information and communication technologies has created sophisticated tools for environmental impact analysis. Some examples are *GaBi* (Europe), *SimaPro* (Netherlands), *MiLCA* (Japan), *DolTPro* (Taiwan), and *eBalance* (China). Of these, *SimaPro* is a mature tool that is well suited for the impact assessment of transportation infrastructure projects (Bachawati et al., 2016). Since *Simapro* was created in 1990, the materials and processes database in this software has been constantly updated to provide a wide range of data for the current case studies of life cycle impact analysis (LCIA) (Starostka-Patyk, 2015). At the same time, *Simapro* also integrates several databases such as the *Ecoinvent*, *ELCD* (European reference Life Cycle Database) and *USLSC* (U.S. Life Cycle Inventory Database), which contain main information concerning production processes for energies, transportation, materials and construction technologies (Caracciolo et al., 2018).

Therefore, Simapro 8.0 was used to analyze the environmental impact of the transportation infrastructure life cycle in this study. In this process, various types of information concerning the construction process and material transportation in the transportation infrastructure in life cycle were adjusted and standardized, and the different environmental impact of different materials were analyzed. In terms of impact analysis, environmental impact was classified into eight types to show the impact of different materials and energies on various environmental indicators in different stages of the life cycle. Finally, a network structure map was built to show the environmental impact of different energies and materials, which can be used to quickly determine the sources of environmental pollution in the whole transportation infrastructure life cycle (Tam et al., 2018).

4 Case study

This study employed the multi-case comparative analysis to explain the environmental impacts of various transportation infrastructure projects throughout their life cycle. Firstly, a comprehensive analysis of each project (case study) was carried out, and their environmental impacts discussed to more comprehensively understand the different characteristics of different types of transportation infrastructure. Secondly, the project information was integrated under a unified general case and the environmental impact of this general case induced and analyzed to provide a more insightful and general description.

4.1 Overview of projects and data collection

As the most important form of transportation infrastructure, highways have a great impact on the environment in every stage of their life cycle. Therefore, five highway projects (including major highways, secondary highways and tertiary highways) were selected from China, Bosnia, and Pakistan. Their major characteristics are summarized in Table 2. Appendix A contains further details of each project.

Table 2. Highway projects summary

ID	Paved area	Design speed	Observations	Number of lanes	Technical specification	Country
Project 1	144,100.0 m^2	80 km/h	The total length is 11 kilometers	Two two-way lanes	Secondary highway	Bosnia
Project 2	9,831.7 m^2	80 km/h	Bridge with a length of 945 m	Two two-way lanes	Secondary highway	Bosnia

Project 3	150,000.0 m^2	60 km/h	An extension to an existing highway	Single two-way lane	Tertiary highway	Pakistan
Project 4	357,484.5 m^2	80 km/h	109 bridges, 5 flyovers, and 8 interchanges	Four two-way lanes	Super highway	China
Project 5	339,150 m^2	100 km/h, 80 km/h	16 interchanges	Four two-way lanes	Super highway	China

The data for all the materials, electricity consumption, fuel consumption, transportation vehicles, construction machinery, and equipment of the five projects were extracted from each engineering project. The complete input data of each functional unit (i.e., 1 m^2 of pavement area) for each project stage is obtained by using equations (1) to (6), combining the energy and materials consumption of each project. Table 3 shows the input of materials in the materialization stage.

Table 3. Input of materials in the materialization stage

Material	Project 1	Project 2	Project 3	Project 4	Project 5
Lime soil/kg	17,989.401	276.390	10,706.510	4,438.414	2,840.694
Gravel/kg	1,511.529	-	11,754.080	34.478	4.031
C20 concrete/m^3	-	-	-	0.200	0.107
C25 concrete/m^3	0.040	-	-	0.058	0.079
C30 concrete/m^3	0.160	1.600	1.002	0.031	-
C50 concrete/m^3	-	3.020	-	0.043	0.106
Asphalt concrete/kg	1,511.529	5,030.413	1,074.308	-	4,036.285
Steel/kg	136.497	985.130	0.180	18.954	45.650
Sand/kg	539.680	7.590	-	-	228.738
Cement mortar/kg	299.680	71.602	-	-	14.926
Coating/kg	17.870	-	-	-	-
Asphalt/kg	-	138.060	-	9.359	-

Note: "-" means the item is not counted in that project (though it may be in other categories).

The transportation measurement and energy consumption of construction during the physical and chemical stage is obtained through equations (1), (3), and (4), and also the energy conversion of equation (6). Table 4 summarizes the results.

Table 4. Energy input and transportation measurement in the materialization stage

Input	Unit	Project 1	Project 2	Project 3	Project 4	Project 5
T_{mj}	$t{\cdot}km/m^2$	380.19	465.91	339.54	317.48	472.20
E_{Pj}	MJ/m^2	15.20	10.95	7.28	9.40	12.90
E_{cop}	MJ/m^2	23.64	17.04	11.32	14.622	20.07

In the maintenance stage, the data input mainly encompasses the energy and materials consumption from daily maintenance and overhaul maintenance. Daily maintenance data is evaluated from the data recorded on the list, whereas equation (5) is used to calculate the value of the overhaul maintenance data. The data shows that daily maintenance consumables only account for 0.003% to 0.08% of the consumables in the materialization stage. Therefore, the consumables in the maintenance stage can be safely ignored. Table 5 provides the results obtained by applying equation (6) by only considering the energy consumption from maintenance activities (by converting them into equivalent calorific values).

Table 5. Energy input during the maintenance stage (in MJ/m^2)

Input	Project 1	Project 2	Project 3	Project 4	Project 5
E_{rj}	0.1945	0.1516	0.7131	0.1636	0.2077
E_{mj}	802.8364	638.7531	679.7739	694.4242	714.9346
E_{tj}	803.0309	638.9047	680.4870	694.5878	715.1423
E_{com}	1,249.1590	993.8520	1,058.5350	1,080.4700	1,112.4440

The data input during the demolition stage mainly consists of energy consumption from demolition and waste transportation. Equations (3) and (4) are used to obtain the energy consumption of the construction machine tools during the demolition stage, while waste transportation is calculated according to equation (2).

Table 6. Energy input and transportation measurement at the demolition stage

Input	Unit	Project 1	Project 2	Project 3	Project 4	Project 5
T_{dj}	*t·km/m2*	190.0900	232.9600	169.7700	158.7400	236.1000
E_{Dj}	*MJ/m2*	87.9018	85.2647	74.4235	82.0417	79.4046
E_{cod}	*MJ/m2*	136.7361	132.6340	115.7699	127.6204	123.5183

SimaPro was used to perform the LCIA by combining the data from Tables 3 to 6.

4.2 LCIA results

In this section, we conducted a comprehensive analysis of each case to understand the environmental impact of different transportation infrastructure projects throughout their life cycle. Tables 7 to 9 clearly show the major impact of each transportation infrastructure on eight types of environmental indicators in three different stages (*materialization*, *maintenance*, and *demolition*).

4.2.1 Results at the materialization stage

Table 7 shows the total environmental emissions of the TI materialization stage.

Table 7. Environmental emissions evaluation indices in the materialization stage

Project	Index	Global warming	Acidification	Eutrophication	Ecotoxicity	Smog	Natural resource depletion	Habitat alteration	Ozone depletion
	Unit	g CO_2 eq	H+ mmole eq	g N eq	g 2,4-D eq	g NOx eq	MJ surplus	T&E count	g CFC-11 eq
Project 1	Emission	2.52E7	9.57E6	81,300	74,100	72,600	31,600	5.97E-10	1.340
	Contribution	49.74%	49.84%	49.86%	49.72%	49.63%	49.84%	49.95%	50.00%
Project 2	Emission	8.32E6	1.33E6	19,500	-13,300	15,600	8,850	1.31E-10	0.369
	Contribution	49.56%	48.92%	49.69%	51.19%	48.53%	49.39%	49.99%	50.00%
Project 3	Emission	3.75E6	1.04E6	7,370	12,900	13,100	11,400	1.87E-11	0.133
	Contribution	48.56%	48.23%	47.89%	48.32%	51.74%	49.28%	48.30%	49.80%
Project 4	Emission	5.98E5	3.47E5	2,080	1,390	4,980	857	4.98E-12	0.048
	Contribution	46.36%	48.09%	45.69%	39.53%	47.94%	47.51%	43.32%	49.60%
Project 5	Emission	1.26E6	3.67E5	1,710	59.5	5,020	1,860	5.15E-12	0.038
	Contribution	47.94%	47.85%	44.71%	6.78%	47.47%	48.53%	43.47%	49.56%

Table 7 shows that the impact of each project on the eight types of environmental indicators is around 50%. For example, the carbon emissions of Project 1 in the materialization stage is 2.52E g CO2 eq, accounting for 49.74% of all carbon emissions in its life cycle. It should be emphasized that large amounts of CO2 emissions are generally considered to be the main cause of global warming (Mintzia et al., 2018). Therefore, the information in Table 7 concerning carbon emissions reflects the contribution of the construction activities (i.e., the materialization stage) of each project to global warming. Similarly, the materialization stage contributes 47.85% ~ 49.84% to the acidification indicator, 44.71% ~ 49.86% to the eutrophication indicator, 47.47% ~ 51.74% to the smog indicator, 47.51% ~ 49.84% to the natural resource depletion indicator, 43.32% ~ 49.99% to the habitat alteration indicator, and 49.56% ~ 50.00% to the ozone depletion indicator. With the exception of Project 5, the materialization stage contributed 39.53% ~ 51.19% to ecotoxicity. Therefore, as expected, it is concluded that the contribution of the materialization stage represents the largest part of the LCIA .

Table 7 also shows that the evaluation results of the eight environmental impact indicators fluctuate in all projects. However, the contribution rate mostly remains relatively stable at approximately 49%. Finally, it is necessary to further analyze the environmental emissions of each material and energy process in the materialization stage. These are shown in Table B1 in Appendix B. In summary:

1) The proportion of steel contributing to the two LCIA indicators of acidification and ecotoxicity is negative, which indicates that steel has an inhibitory effect in the process of acidification and ecotoxicity.
2) Lime soil is responsible for a large proportion of the environmental impact in all evaluation indices. The environmental contribution rate of Project 1, for example, is always >95%. Therefore, attention needs be paid to the environmental emissions caused by the use of lime soils as a construction material.

3) Comparing the results of the materials and energy processes, the main factors influencing environmental impact are steel, asphalt concrete, C20 concrete, C30 concrete, and C50 concrete.
4) Four types of concrete (C20, C25, C30, and C50) have the same amount of influence on the eight LCIA indicators. However, the four kinds of concrete have the greatest impact on ecotoxicity in the evaluation indices.
5) Lime soil, asphalt concrete, paint, crushed stone, sand, and other materials have the largest impact on the acidification index; cement mortar, C20, C25, C30, and C50 concrete have the greatest impact on the ecotoxicity indicator; while reinforcement steel, asphalt, and construction energy consumption have the greatest impact on habitat alteration, natural resource depletion, and ozone depletion.

4.2.2 Results during the maintenance stage

Table 8 shows the total environmental emissions during the TI maintenance stage.

Table 8. Environmental emissions during the maintenance stage

Project	Index	Global warming	Acidification	Eutrophication	Ecotoxicity	Smog	Natural resource depletion	Habitat alteration	Ozone depletion
	Unit	g CO_2 eq	H+ mmole eq	g N eq	g 2,4-D eq	g NOx eq	MJ surplus	T&E count	g CFC-11 eq
Project 1	Emission	2.54E7	9.61E6	8.17E4	7.48E4	7.32E4	3.17E4	5.98E-10	1.3400
	Contribution	50.13%	50.05%	50.11%	50.19%	50.04%	49.99%	50.04%	49.99%
Project 2	Emission	8.41E6	1.37E6	1.97E4	-1.28E4	1.61E4	8.97E3	1.31E-10	0.3690
	Contribution	50.10%	50.39%	50.20%	49.26%	50.09%	50.06%	49.99%	49.99%
Project 3	Emission	3.89E6	1.09E6	7.85E3	1.36E4	1.16E4	1.16E4	2E-11	0.1340
	Contribution	50.38%	50.55%	51.01%	50.95%	45.81%	50.14%	51.66%	50.18%
Project 4	Emission	6.71E5	3.68E5	2.43E3	2.04E3	5.27E3	917	6.37E-12	0.0488
	Contribution	52.10%	51.00%	53.38%	58.02%	50.74%	50.83%	55.41%	50.32%
Project 5	Emission	1.34E6	3.91E5	2.07E3	723	5.36E3	1.93E3	6.55E-12	0.0383
	Contribution	50.99%	50.98%	54.13%	82.38%	50.69%	50.35%	55.29%	50.35%

In the maintenance stage of Project 1, for example, the carbon emissions contributing to the global warming indicator are 2.54E7 gCO_2 eq, accounting for 50.13% of Project 1's life cycle carbon emissions. These figures highlight again the carbon emissions' high contribution rate to global warming during the maintenance stage. Overall, the contribution rate of each of the five projects to the eight indicators remains stable at around 50% with little fluctuation. The only exception is the ecotoxicity indicator for Project 5, which peaks at 82.38%.

4.2.3 Results during the demolition stage

Table 9 shows the total environmental emissions during the demolition stage.

Table 9. Environmental emissions in the demolition stage

Project	Index	Global warming	Acidification Eutrophication	Ecotoxicity	Smog	Natural resource depletion	Habitat alteration		Ozone depletion
	Unit	g CO_2 eq	H+ mmole eq	g N eq	g 2,4-D eq	g NOx eq	MJ surplus	T&E count	g CFC-11 eq
Project 1	Emission	6.46E4	2.12E4	56	142	494	109	1.47E-13	7.36E-5
	Contribution	0.13%	0.11%	0.03%	0.10%	0.34%	0.17%	0.01%	0.01%
Project 2	Emission	5.69E4	1.9E4	41.4	117	442	98.3	6.97E-14	3.34E-5
	Contribution	0.34%	0.70%	0.11%	-0.45%	1.38%	0.55%	0.03%	0.01%
Project 3	Emission	8.17E4	2.64E4	169	195	621	134	1.6E-14	4.2E-5
	Contribution	1.06%	1.22%	1.10%	0.73%	2.45%	0.58%	0.04%	0.02%
Project 4	Emission	2.09E4	6.6E3	42	86	137	29.9	1.47E-13	7.19E-5
	Contribution	1.62%	0.91%	0.92%	2.45%	1.32%	1.66%	1.28%	0.07%
Project 5	Emission	2.8E4	8.98E3	44.3	95.1	195	42.8	1.47E-13	7.22E-5
	Contribution	1.07%	1.17%	1.16%	10.84%	1.84%	1.12%	1.24%	0.09%

The contribution rate of the environmental evaluation indicators to the life cycle environmental emissions in the demolition stage is generally below 2%. This shows that the demolition stage makes the smallest contribution of the three stages. However, the environmental emissions of each evaluation index are not directly proportional to the contribution rate: when environmental emissions are large, it does not mean that the contribution rate is also large − this is because the contribution rate is related to the total environmental emissions in the life cycle.

4.3 Net structure analysis of the LCIA

Figure 2 shows the network structure diagram of the combined average material input and energy input of the five projects, clearly indicating the environmental impact contributions of the main material flows and energy flows in the TI LCIA. The material and energy branches in the materialization stage are complex, with the largest proportion accounting for 99.3%. Secondly, the maintenance stage accounts for 0.3%, whereas the proportion of the demolition stage is 0.4%. The mesh structure diagram clearly shows the key stages and processes of emission reductions. It also provides the basis to support the adoption of the emissions reduction measures discussed in the next section.

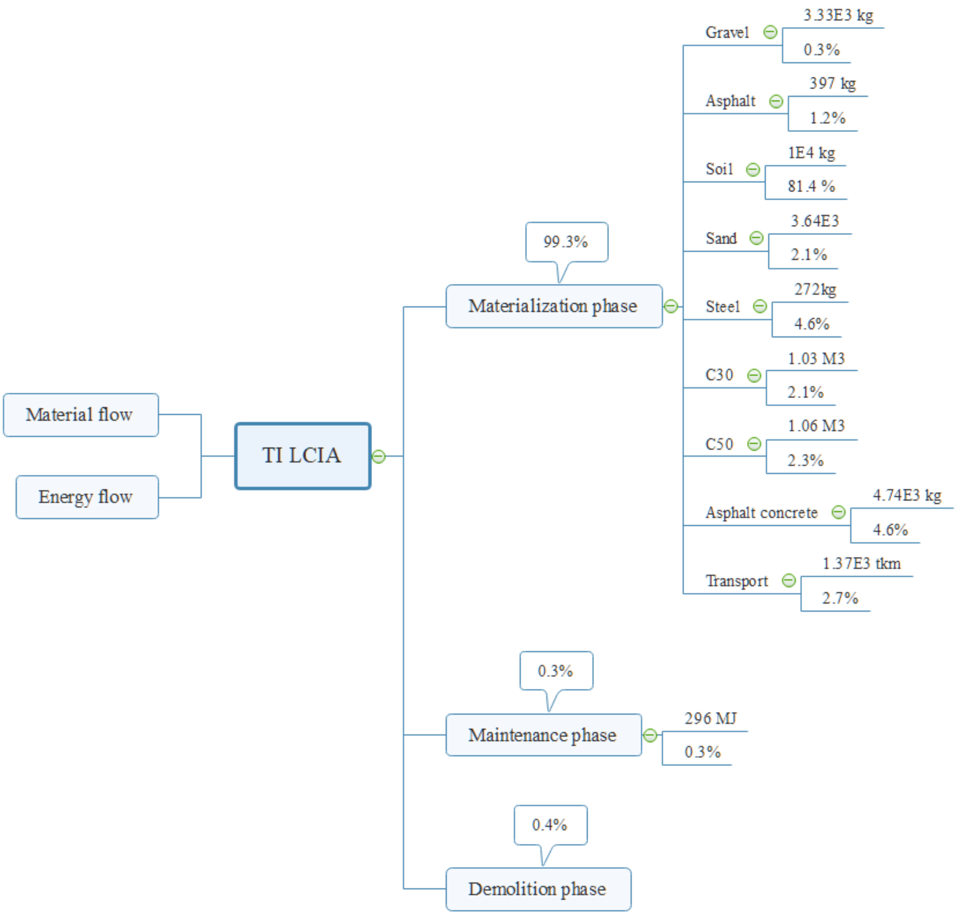

Figure 2. Network structure of the TI LCIA (average input from the 5 projects)

5 Policy recommendations

The environmental impact assessment of the life cycle of transportation infrastructure indicates that the environmental pollution of transportation infrastructure is mainly caused by a large amount of resources and energy consumption – suggesting the following three policy recommendations:

1. *Establish a standard system of transportation infrastructure construction.* The rapid development of transportation infrastructure has led to an increase in environmental pollutant emissions. However, the most serious environmental problems are created during the materialization stage of transportation infrastructure: the source of transportation infrastructure environmental pollution mostly lies in the choice of resources and energy used. An alternative is to propose a standard system of transportation infrastructure construction. This standard system would constitute a

benchmark or baseline against which authorities could compare the materials, sources of energy, and technical equipment actually used in the project materialization stage. It would also be a way for governments to regulate the construction market, promote the technical progress, and improve construction standards. At the same time, indicators of sustainable development of transportation infrastructure could be built, including the resources consumed by each square meter of transportation infrastructure and ensuing environmental emissions.

2. *Introduce incentives for green technology innovation and product innovation.* Innovations in building materials and construction technologies − encouraging the development and promotion of low-carbon technologies and green materials − are important ways to effectively curb environmental pollution at its source. To achieve this, it is firstly necessary to strengthen the exchange and cooperation between innovative talents, which is not only conducive to the cultivation of talents, but also conducive to the innovation and diffusion of advanced technologies. Then, to build trading platforms of green technology and green products; green technology (product) trading platforms provide a variety of materials and technology choices for construction. This helps contractors and project designers to choose technologies and products flexibly according to the needs of each transportation infrastructure project, and effectively reduces the economic cost of environmental protection. At the same time, the expansion of green technology can also stimulate investment in innovation and accelerate the pace of technological progress. Furthermore, an intellectual property protection system needs to be established, as the protection of intellectual property rights can effectively stimulate innovation behaviors. The legal systems need to be improve to preserve the innovation activity growth by discouraging companies from infringing intellectual property rights.

3. *Implement a transportation infrastructure long life security system*. Transportation infrastructure need to be continuously improved and maintained to keep/restore its original functionality. Based on modern information technology, timely repairs of

damaged areas are attainable within daily preventive maintenance operations. The analysis in the present study shows how overhaul maintenance generates significantly more emissions than preventive daily maintenance. Hence, the latter needs to be favored whenever possible, with such specific methods as real-time monitoring by combining artificial intelligence technology and remote sensing technology.

6 Conclusions and future work

In order to fully evaluate the environmental impact of transportation infrastructure, this study analyzes the environmental impact of five international case studies based on life cycle analysis theory and policy recommendations are made to reduce the environmental emissions of transportation infrastructure. The main conclusions are as follows.

1. High consumption of materials and energy is the main cause of environmental pollution from transportation infrastructure, especially during the materialization stage. Namely, the fabrication/extraction of steel, lime soils, asphalt, and all kinds of concrete are the main sources of environmental emissions. In particular, lime soil has the greatest influence on the environmental evaluation indices, whereas steel has an inhibitory effect on acidification and ecotoxicity. Therefore, to reduce unnecessary material consumption and minimize environmental pollution, it is necessary to have on-site controls mostly during the construction stage, limit the use of highly pollutant materials, and increase the amount of green innovative materials.
2. Frequent overhaul maintenance has a much greater impact on the environment than preventive daily maintenance. Overhaul maintenance consumes a great amount of materials and energy, resulting in more environmental emissions. In the maintenance stage of the five projects analyzed, the contribution rate of emissions

was approximately 50% − mostly caused by Overhaul maintenance. Therefore, regular preventive daily maintenance needs to be favored whenever possible.

This study is limited by not distinguishing between different types of transportation infrastructures. Hence, future studies could divide transportation infrastructure into highways, railways, ports, airports, etc., to explore the environmental impacts of these different types. Second, in the process of analyzing environmental emissions during the life cycle of transportation infrastructure, this study focuses solely on the input of major materials and energy sources at various stages and not the contribution of less common or alternative materials. Future research needs to consider the impact of these materials to build a more comprehensive LCIA model.

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